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ORIGIN OF THE PEGMATITES OF MAINE[1]

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During a portion of the summers of 1906 and 1907 I had the opportunity to study in some detail the pegmatite deposits of Maine, and at intervals during succeeding years have been able to pay brief visits to commercially important pegmatite deposits in Connecticut, New York, Pennsylvania, and Maryland. Without entering into the details of the field occurrences, which will be described in a forthcoming bulletin of the U.S. Geological Survey, I wish to summarize here the more important scientific results of these studies. Particular acknowledgment is due to Dr. Whitman Cross of the U.S. Geological Survey, for valuable criticism and advice in this work.

The pegmatite deposits in the state of Maine all belong to the type commonly known as granite pegmatite, its dominant minerals being the same as those which are most abundant in ordinary granites. Pegmatites are most abundantly developed in the western and southwestern part of the state, and are invariably associated with granites. Excellent exposures in the feldspar and gem quarries, on glaciated ledges, and especially along the seashore in the Boothbay Harbor region, afford unusual opportunities for detailed field studies.

General geologic relations.—The pegmatite masses vary in size from extremely small stringers intimately injected between the foliae of schists and thus forming injection gneisses, to batholitic masses

[1] Published with the permission of the Director of the U.S. Geological Survey.

a mile long and one-half mile wide, showing coarse pegmatitic textures throughout. Most commonly the pegmatite masses are roughly lens-shaped and lie parallel to the foliation of the inclosing schistose rocks, their attitude being dikelike or sill-like, according as the schists lie at steep or gentle inclinations.

The rocks associated with the pegmatites are granite gneiss, granites of various textures, and schists of sedimentary origin. The field relations show that the pegmatites are invariably intrusive into the sedimentary schists, frequently cutting sharply across the schist foliae though usually intruded parallel to them. Characteristic contact metamorphic minerals are sometimes developed. Into the granite gneisses the pegmatites are also in some instances distinctly intrusive, but in other cases their relations indicate that the two rocks are nearly contemporaneous and probably related in origin.

The relations between the pegmatites and the granites indicate beyond reasonable question that the two rock types are genetically related. Evidence of this is found (1) in the fact that the predominant minerals in both rocks are the same; (2) in the occurrence of granite in all districts where pegmatites are found, and (3) in numerous observed instances of transition from granite to pegmatite. One of the most instructive instances illustrating such transition is exposed on the shore of Boothbay Harbor, and is illustrated in Fig. 1. Microscopic examination of the fine-grained granite and the pegmatite in this occurrence shows that the mineral species in the two rocks are identical, the sole differences being in the texture and the proportions of the constituents. In other instances small irregular segregation-like masses with pegmatitic texture are wholly inclosed by normal granite. Although in certain instances distinct dikes of pegmatite cut the granites and in other instances dikes of granite cut the pegmatites, there is no evidence that the two rocks are of widely different ages or that there was more than one general period of granite and pegmatite intrusion. The granites are known to be of late Silurian or early Devonian age, and it is probable that the pegmatites are to be similarly correlated. With the exception of certain diabases, the granites and pegmatites are the youngest known igneous rocks of the state.

Mineral composition and texture.—As already stated, the dominant

pegmatite minerals are those characteristic also of the normal granites; namely, quartz, orthoclase and microcline, albite or oligoclase, muscovite, biotite, and black tourmaline. Accessory constituents nearly always present are garnet, magnetite, and green opaque beryl. Accessory minerals which are present only in certain pegmatites number

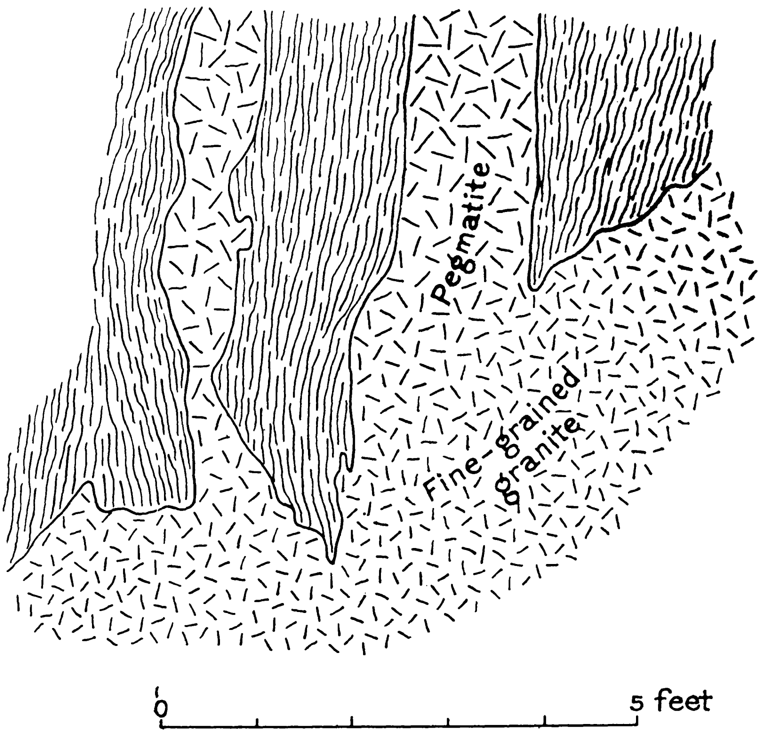

FIG. 1.—Granite grading into pegmatite and both intrusive in schists. Shore of Southport Island near south entrance of Townsend Gut.

over fifty species; the most important are lepidolite, amblygonite, spodumene, blue, green, and pink tourmaline, transparent blue, green, or golden beryl, colorless to amber-colored topaz, and rose and amethystine quartz. A number of pegmatites have been successfully worked for certain of these gem minerals.

In possibly ninety-nine one-hundredths of the pegmatite masses in the state no unusual minerals are present, the constituents being the same as in the normal granites and the proportions also somewhat

similar. The principal variations in composition involve (1) an increase in silica, (2) an increase in sodium and lithium, and (3) an increase in fluorine. The increase in silica content manifests itself in a greater abundance of quartz. Pegmatites unusually rich in quartz are less common in Maine than in certain other pegmatite districts of the eastern United States, but it is quite possible that many of the quartz dikes occurring in southern Maine were derived from pegmatite

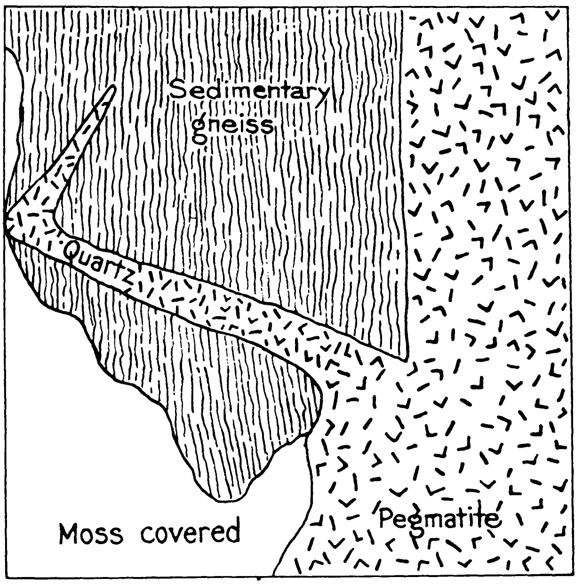

FIG. 2.—A quartz offshoot from pegmatite, 2½ miles northeast of Paris. The branch vein is pegmatite for a short distance beyond the main pegmatite mass, but beyond this grades into pure quartz. The area illustrated is about 4 feet square.

magmas. This is suggested by the fact that certain of these masses contain occasional crystals of feldspar, black tourmaline, or beryl. In one instance, the transition from pegmatite to quartz vein, illustrated in Fig. 2, was observed. The second variation, involving an increase of sodium and lithium, shows itself in the development of occasional pegmatite masses which are rich in albite, lepidolite, spodumene, colored tourmaline, and amblygonite. The tourmaline mines of the state are in deposits of this type. The third variation, involving an increase in the fluorine content, is exemplified by occasional pegmatite masses which contain topaz, fluorite, herderite, hamlinite,

certain types of apatite, etc. Increase either in sodium and lithium or in fluorine is usually accompanied by an increase in phosphorus content. The pegmatite characterized by these rarer minerals constitutes only an exceedingly small part of the total volume of pegmatite in any district.

In coarseness, the pegmatites vary from little coarser than normal granites to masses showing single crystals of feldspar 20 feet across. Their distinguishing feature is therefore not coarseness but extreme irregularity of grain. Distribution of the constituent minerals in bands, such as is observed in pegmatites in some other regions, is entirely absent in Maine, the minerals usually (except for the graphic intergrowths) being distributed with complete irregularity. Graphic intergrowths are very abundant and include those of quartz with feldspar and less frequently of quartz with muscovite, feldspar with muscovite, garnet with quartz, black tourmaline with quartz, and spodumene with quartz. All of these intergrowths may occur in the same pegmatite mass.

Cavities are practically absent from the finer-grained pegmatites, and in most of the coarse-grained pegmatites constitute less than 1 per cent of the total volume. The gem-bearing pegmatites, however, are usually characterized by a central zone in which albite, lepidolite, tourmaline, amblygonite, etc., are particularly abundant and in which miarolitic cavities are also quite abundant. It is on the walls of such cavities that the gem tourmalines were developed. At Mt. Mica, which is the largest and most famous tourmaline locality in Maine, the largest pocket found was $20 \times 12 \times 7$ feet, but the majority do not average more than a foot or two in diameter. Only a few of these pockets contain gem minerals in any considerable amounts, but groups of quartz crystals are developed on the walls of many others.

Origin.—The writer does not purpose in this article to attempt a discussion of the voluminous literature on pegmatites except in so far as it bears closely upon those of the region under discussion. Previous writings and theories have been well summarized by George H. Williams[1] and especialy by Brögger.[2]

[1] George H. Williams, *Fifteenth Ann. Rept. U.S. Geol. Survey*, 675–84.

[2] Brögger, "Der Syenitpegmatitgange der südnorwegischen Augit und Nephelinsyenite," *Zeitschr. f. Kryst.*, XVI (1890). Sections on genesis translated in *Canadian Records of Science*, VI (1894), 33–46, 61–71.

If, as seems necessary from the field evidence, we admit a genetic connection between the pegmatites and granites, it is next of importance to inquire what evidence is afforded by the Maine pegmatites as to the physical and chemical conditions which resulted in the crystallization, from related magmas, of rocks of such widely varying character.

Influence of external conditions.—Differences in external conditions at the time of crystallization appear inadequate to explain the observed textural differences. This is shown by the close associations of the two types of rocks, already cited as evidence of their genetic relationships. The field relations show that in many instances the external conditions, such as the nature and temperature of the wall-rock, depth at which solidification took place, etc., were similar for both types of rocks. In cases, such as shown for example in Fig. 1, the general external conditions must have been practically the same for both rocks. A similar conclusion is justified in numerous other instances where granite and pegmatite grade into each other and especially in cases where pegmatite forms segregation-like masses wholly inclosed in granite. Conversely, the broad general similarity of the pegmatites over very large areas where the external conditions were certainly *not* constant also indicates that the causes of their peculiar textures were in the main internal rather than external. It seems necessary to look therefore to differences inherent in the magmas themselves for an explanation of the textural variations.

Influence of dominant constituents.—The characters shown by the Maine pegmatites accord with the evidence obtained from many other districts in indicating that the pegmatite magma were characterized as a general rule by the presence of certain components in larger amounts than in normal granite magmas and that these differences in composition were in large measure responsible for the differences in texture. The exact nature of such differences is, however, more largely a matter of inference than of direct field observation.

In the great mass of the pegmatite, what may be termed the *normal* pegmatite, it is exceedingly difficult, if not impracticable, to make a satisfactory estimate of the relative proportions of the different mineral constituents, but as far as can be judged without measurements the proportions are of the same general order as in the normal granites,

except that the pegmatites are probably on the average slightly more quartzose, a conclusion which seems warranted by the frequent transitions from pegmatite masses into veins composed largely or wholly of quartz. As is well known, the highly quartzose types show as typical pegmatitic textures as the less quartzose. The difference in the proportions of the *principal* mineral constituents in the normal granites and the normal pegmatites seems, therefore, insufficient to account for the great difference in their textures. It appears necessary to seek the cause of these contrasts in differences in the proportions of minor constituents or in the presence in the granite or pegmatite magmas of constituents which have since escaped, or which through occlusion are not now visible to the unaided eye, in the derived rocks.

Influence of minor constituents.—The presence in many pegmatites of unusual minerals, such as fluorite and other fluorine-bearing minerals, lithium minerals, boron and phosphorus minerals, and occasionally the rare earth minerals, has led certain geologists[1] to attribute to some of these substances an important rôle in the production of pegmatite textures. It cannot be doubted that when present in magmas such substances have some influence upon the texture of the resulting rock. It has not been demonstrated however that the presence of these unusual constituents is essential to the development of typical pegmatitic textures. In the opinion of the writer their presence is probably *not* essential. The pegmatites which earliest attracted the attention of American mineralogists and geologists and which have been most often described in the literature were naturally those in which unusual minerals were present in especial abundance or in perfection of crystal form. Such pegmatites constitute, however, only an exceedingly small proportion of the pegmatite in any district and must be regarded as unusual rather than normal types. The writer is familiar with certain deposits showing typical pegmatitic textures, which have been worked for their feldspar for years with the discovery of few if any of the rarer minerals.[2] In the great majority of the pegmatites of Maine unusual minerals are of

[1] Certain French geologists in particular have been advocates of this view. See De Lapparent, *Traité de géologie*, 4th ed., 639 (1900); and De Launay, *La science géologique*, 557–58, 582–83 (1905).

[2] The Andrews feldspar quarry in Portland, Conn., the Frost feldspar quarry in Maryland, and the Goldings feldspar quarry in Georgetown, Maine, are examples. See *Bull. U.S. Geol. Survey No. 420*, 31, 50, and 75.

such infrequent occurrence as ordinarily to escape detection entirely. In pegmatities where they are present their paucity or abundance seem to have small influence on the textures developed. Those inclined to attribute large influence in the development of pegmatitic textures to the presence of rare constituents usually contend that a more careful study will show that their scarcity is apparent rather than real. Such an assumption is not in accord with the field observations of the writer in Maine and other parts of New England, and appears unwarranted.

Influence of gaseous constituents.—If neither the dominant nor the rare minerals of the pegmatites have been controlling factors in the development of typical pegmatitic textures, it appears necessary to seek an explanation in the presence in the magmas of certain constituents which have subsequently escaped or at least are not readily recognized in the resultant rock. The fact that large crystals cannot be obtained at atmospheric pressures from simple dry melts of the commoner rock-forming minerals suggests at once that the crystallization of these minerals in nature took place either under widely different physical conditions (such as high pressure) or in the presence of certain substances which are scarce or absent in the rocks as now exposed. It has already been shown from field evidence (p. 302) that in many instances differences in pressure or other external conditions at the time of crystallization cannot reasonably be appealed to, to explain the textural variations observed. In such cases an appeal to the escaped constituents of the magma appears unavoidable. The same conclusion appears necessary when we consider the extreme viscosity exhibited (under atmospheric pressures) by silica, orthoclase, and albite near their melting temperatures. The various forms of silica which have been artificially produced have all crystallized from a melt so viscous as to be virtually a glass.[1] In the case of orthoclase the viscosity of its melt is so great that all attempts to crystallize the mineral from it have been unsuccessful. Since increase in pressure *per se* can hardly be appealed to as increasing molecular mobility[2]

[1] See Day and Shepherd, "The Lime-Silica Series of Minerals," *Amer. Jour. Sci.*, XXII, 271–73 (1906). Also Day and Allen, "The Isomorphism and Thermal Properties of the Feldspars," *Publications of the Carnegie Institution of Washington No. 31*, 28–29, 45–55 (1905).

[2] See Harker, *The Natural History of Igneous Rocks*, 163–64 (1909).

in magmas, it seems necessary again in accounting for the large crystals developed in the pegmatites to postulate the presence in the magma of some substance or substances not now recognizable in the derived rock. That the presence of volatile constituents in a magma does influence the viscosity is shown by the fact that certain obsidians may be readily melted with evident fluidity and the escape of gases, but that their refusion after such gases have escaped is much more difficult. Prof. Iddings[1] has also shown from a microscopic study of the obsidian of Obsidian Cliff, Yellowstone National Park, that where there was more dissolved gas the conditions were more favorable for crystallization than in other parts of the magma.

Among those constituents of magmas which might escape, leaving little record of their former presence, water gas and hydrogen are probably the most abundant, as is plainly indicated by analyses of the gases still remaining in igneous rocks[2] and by studies of the gases emitted from volcanic vents.[3]

The presence of water gas in association with subordinate amounts of other gases and of certain unusual substances (mineralizers) has been considered by many observers to be the competent and effective cause in the development of pegmatitic textures. With this opinion the present writer is in general accord, though the persuasion is based more largely upon the process of reasoning already outlined than upon field evidence of high water content or relatively low viscosity in pegmatite magmas. The field evidence gathered in the study of the Maine pegmatites must be looked upon as merely suggestive; anything like a complete solution of the problem will in all probability wait upon synthetic laboratory experiments upon the interaction between gases and rock-forming silicates.

The small weight of the gaseous and liquid constituents of most igneous rocks as compared with the total weight of the rock might lead one to question their competence to affect notably the viscosity

[1] J. P. Iddings, *Seventh Ann. Rept. U.S. Geol. Survey*, 283–87 (1888); *idem*, *Igneous Rocks*, 185 (1909).

[2] See R. T. Chamberlin, "The Gases in Rocks," *Publications of the Carnegie Institution of Washington No. 106* (1908). This includes a summary of earlier investigations.

[3] For a review of the literature on volcanic gases, see Clarke, "The Data of Geochemistry," *Bull. U.S. Geol. Survey No. 330*, chap. viii (1908).

of magmas and to produce large textural variations. In this connection it may not be out of place to call attention to a possible application of Raoult's Law.[1] This law states that if various substances are dissolved in equal amounts of the same solvent in the proportions of their molecular weights the resulting lowering of the freezing-point of the solution will be the same in each case.[2] In other words the effect produced is a function of the number of molecules concerned and is not primarily dependent on the nature of the substances introduced. It follows that a small amount by weight of a substance of low molecular weight (such as H_2O, mol. wt. 18) will exert the same depressing influence on the freezing-point of the solution as a much greater weight of a substance of high molecular weight (such as Fe_2O_3, mol. wt. 160), and that given equal weights of the two, the substance of low molecular weight will exercise much the greater influence. This law has been found to apply strictly only to very dilute solutions where there is no chemical action between solvent and dissolved substance. It has been applied bodily by Vogt[3] to rock magmas, but the wisdom of such extension to cover widely different and much more complex physical conditions may well be questioned. It seems not unreasonable, however, to attribute some general importance to this principle in rock magmas, to the extent that magmatic constituents of low molecular weight may exert greater influence in lowering the freezing-point, decreasing viscosity, and affecting textures than constituents of high molecular weight. They may thus attain an importance which appears disproportionate to the small part by weight which they form of the whole magma. The substances (hydrogen, water, fluorine, chlorine, and boron) commonly believed to exert the greatest influence upon the viscosity of magmas and the textures of the resulting rocks are all substances of much lower molecular weights than silica and the rock-making silicates and oxides, even when the minimum values for the latter are assumed. The hiatus between the molecular weights of these two groups of substances is so marked as to justify the retention of the term "mineralizers" for the lighter group, in case the

[1] See Ostwald, *Outlines of General Chemistry*, 136–37 (1895).

[2] Neglecting electrolytic dissociation, which is probably of small importance in rock magmas.

[3] See Vogt, *Die Silikatschmelzlosungen*, II, 128–35 (1904).

principle outlined above is eventually shown to be operative to an important degree in magmas. It is perhaps unnecessary to add that other causes besides low molecular weight may be effective in reducing viscosity in magmas.

Field and laboratory evidence bearing upon viscosity and gas content.—The field and laboratory data on the pegmatites of Maine which bear upon the viscosity or gaseous content of the pegmatite magmas may be set forth as follows. Since the pegmatite magmas crystallized at some distance below the surface, the gases which they contained must either have made their escape through the wall-rocks or else have remained in cavities or occluded within the solid pegmatite mass. The escape of such materials through the wall-rocks should presumably leave some record in contact metamorphic effects. Their retention within the rock should presumably be recorded in an especial abundance of miarolitic cavities and fluid or gaseous inclusions. The field studies of the writer in Maine and other parts of New England show that the granites are almost wholly devoid of miarolitic cavities of any kind. An isolated cavity of small size is occasionally met with but its walls are usually more or less pegmatitic in texture. In the great bulk of the pegmatites of Maine, particularly the finer-grained ones, such cavities are also exceedingly rare. In the coarser pegmatites, however, they are a characteristic feature, though usually, as far as can be judged, constituting considerably less than 1 per cent of the total volume of the pegmatite. Within the very limited gem-bearing zones of certain pegmatites miarolitic cavities may form a considerably larger percentage of the total volume. Such cavities have been attributed by various writers to shrinkage of the pegmatite mass in crystallization. This may in fact play some part in their formation but that they are not entirely the result of shrinkage but on the contrary were filled or partly filled with some material which has since disappeared, is shown by the presence of perfectly developed crystals of quartz, tourmaline, and other minerals projecting inward from the walls of the cavities. Some filling must have been present from which such crystals derived the materials for their growth. It is probable therefore that immediately after the crystallization of the main body of pegmatite the miarolitic cavities were completely filled with a gaseous solution which may later have liquefied and has since

disappeared. Water gas probably formed the bulk of this cavity filling, though carrying numerous other substances in solution. The abundance of quartz crystals on the walls of these cavities indicates that silica was one of the most abundant of these dissolved substances.

If the presence of larger amounts of gaseous constituents is responsible for the crystallization of the rock with pegmatitic rather than granitic texture, we might reasonably expect greater size or abundance of microscopic fluidal or gaseous cavities in the pegmatite minerals than in those of the normal granites. With this idea in mind the writer attempted a microscopic measurement of these inclusions in pegmatites and associated granites from Maine. On account of the uneven distribution of the inclusions in bands traversing the minerals accurate estimates were found to be impracticable and the results were negative or inconclusive. It was found moreover that some of the bands of fluidal cavities in the quartz of pegmatite were formed later than shearing movements which had affected the quartz. The inclusions in the pegmatite were similar in character to those in the normal granites of Maine, and any differences in their size and abundance in the two types of rocks were not sufficient to be noted on casual inspection.

If the pegmatite magmas are characterized by considerably larger proportions of gaseous constituents than are present in the granite magmas, we might expect notable differences in the contact metamorphic effects produced by the two types of rocks, since such effects are believed to be produced largely by gaseous and fluid emanations from the cooling igneous masses. Field observations in Maine fail to show that contact metamorphic effects, due to the intrusions of pegmatite, are notably greater than those produced by the granites. The effects produced by both are usually slight and in many instances almost nil. Masses both of pegmatite and granite frequently cut across the foliation of schists without any distortion of the latter, the contacts being of knife-edge sharpness. In other instances pegmatite has produced some softening of the bordering rock. Such effects are confined however to the immediate vicinity of the pegmatite, usually to a zone a few inches in width, and are the exception rather than the rule, most pegmatite contacts being exceedingly sharp and free from all evidence of softening. Absorption (except in a few doubtful instances) appears to be wholly absent, the contacts, even in the cases

where softening is shown, being sharp, and the pegmatite next the contact showing no difference in composition from that at some distance away. Where schist fragments are inclosed in the pegmatite their sharp outlines are preserved.

If the physical conditions of the pegmatite and granite magmas were notably different at the time of their intrusion, it would be natural to expect some differences in the forms assumed by the granite and pegmatite masses. While in many cases the forms assumed by the two types of rocks are similar there is in general a tendency for the smaller pegmatite intrusions in the foliated rocks to assume the form of a succession of lenses while granite intrusions of similar size tend to be more nearly parallel-walled. This contrast is particularly noticeable in the Boothbay Harbor region and near Rumford Falls and is probably expressive of slightly greater rigidity in the granite than in the pegmatite magma and also of greater softening of the inclosing schist by the pegmatite than by the granite magmas. The great size of certain pegmatite masses, such as Streaked Mountain in Hebron, is on the other hand suggestive of physical conditions in some pegmatite magmas not widely different from those obtaining in normal granite magmas. The crest of Streaked Mountain was examined for over half a mile of its length, and the width of outcrop examined across the trend of the ridge was also about half a mile. The whole area traversed and the remainder of the mountain as far as it could be seen was underlain almost exclusively by coarse pegmatite, the mountain being a "boss" of this material. The pegmatite is of the usual granitic type and exhibits no more than the usual amount of variation in texture and composition from point to point. It is difficult to conceive of a mass of this size and general uniformity crystallizing under anything like vein conditions. With very high gaseous content and correspondingly high mobility it would be natural to expect more differentiation both in texture and composition. It seems probable that the specific gravity and the viscosity of such a pegmatite magma was not so much below that of a granite mass intruded under similar conditions as has been commonly supposed.

Fragments of the wall-rock are very frequently inclosed by the border portions of the granite masses of Maine. The phenomenon

is much less common in the case of the pegmatites, but was nevertheless observed at several localities. On the highest portion of Streaked Mountain a number of patches of schist a few square yards in area were seen apparently entirely inclosed by pegmatite. Small schist fragments are also inclosed by pegmatite in the Boothbay Harbor region. Dr. W. H. Emmons of the U.S. Geological Survey, who visited Mt. Mica a year later than the writer, when the excavation had proceeded farther, observed schist fragments in the pegmatite there a few feet below the schist hanging wall. These appeared to have been wholly inclosed by pegmatite, and the schistosity of the fragments made large angles with the schistosity of the walls from which they were evidently dislodged. The pegmatite shows no bending of the minerals or other changes in character near the fragments. In the instances cited the schist fragments appear to have been caught up while the pegmatite mass was still partly or wholly fluid, and *the specific gravity of the magma was sufficient, at least in the Mt. Mica example, to float the fragments.*

Temperatures of pegmatite crystallization.—Some evidence in regard to the temperatures of the pegmatites at the time they crystallized has been obtained from studies of quartz by Wright and Larsen,[1] a number of the specimens being collected by the writer from the pegmatites of Maine and other parts of New England.

Studies of these writers and of earlier observers have shown that at about 575° C., quartz undergoes a sudden change from one form of crystal symmetry to another. Wright and Larsen have defined the criteria which may be applied to distinguish the quartz which crystallized below 575° and that which crystallized above that temperature and has undergone reversal in the solid state upon cooling.

No granites of Maine were tested by these experimenters, but thirteen specimens of granite gneisses and quartz porphyries from other regions show as a rule the characters of high-temperature quartz, thus placing their final crystallization above 575° C.

Quartz from a dike of fine-grained pegmatite from one to four feet wide, which intrudes biotite granite near Rumford Falls, is of the high-temperature variety. This dike is typical of many of the

[1] F. E. Wright and E. S. Larsen, "Quartz as a Geologic Thermometer," *Amer. Jour. Sci.*, XXVIII (June, 1909), 423–47.

finer-grained pegmatite bodies of the state. Tests of the quartz from graphic granite in the quarry at Topsham, Maine, and a similar graphic granite collected by the writer from Portland, Conn., also showed high-temperature characteristics. Similar results were obtained with graphic granite from the Urals in Russia.

In contrast to the high temperature of formation indicated by these quartzes, tests upon specimens of rose quartz from the Maine pegmatites and from typical granite pegmatite at Bedford, N.Y.,[1] indicated crystallization at temperatures below 575°. Similar low-temperature characteristics were also exhibited by a sample from a large mass of white quartz from Topsham, Maine. This graded into quartz of graphic granite which when tested showed high-temperature characters. Quartz from a cluster of well-defined crystals occurring in a miarolitic cavity in pegmatite in Topsham showed low-temperature characteristics. This quartz group interlocked at its base with the feldspar of the wall of the pocket and plainly crystallized with the rest of the pegmatite mass. Quartz associated with lepidolite and albite in the gem-bearing portion of pegmatite from Poland, Maine, showed low-temperature characteristics. A pyramid-tipped prism of quartz from Topsham, projecting into a feldspar crystal in the midst of coarse pegmatite and plainly a contemporaneous crystallization, showed low-temperature characteristics. Crystals of smoky quartz from Poland, developed on the walls of pockets, showed low-temperature characteristics.

The results of these tests are consistent among themselves and in accord with the order of crystallization of various portions of the pegmatite established by field evidence. While it is unsafe to draw sweeping conclusions from a rather small number of tests, these are nevertheless highly suggestive, and render it very probable that while many of the finer-grained pegmatite masses crystallized above 575° C., certain portions of the coarser pegmatites crystallized at lower temperatures. In these coarser pegmatites the graphic intergrowths of quartz and feldspar crystallized above 575° C., while the coarser and more siliceous portions characterized by cavities, and probably richer in gaseous or fluid constituents, crystallized below 575°. Since

[1] Edson S. Bastin, "Feldspar and Quartz Deposits of Southeastern New York," *Bull. U.S. Geol. Survey No. 315*, 395–98.

portions showing high- and low-temperature characteristics are frequently intimately associated in the same pegmatite mass, we have here furnished a key to the general temperature of solidification of many of these bodies, namely in the neighborhood of 560–80° C.

Eutectics in pegmatites.—Largely as a result of the extensive studies of Vogt[1] many geologists[2] have been led to attribute an important rôle to eutectics in rock formation. One of the first[3] phenomena to suggest such a relation was obviously the graphic structure exhibited by many pegmatites, which closely resembled patterns formed by eutectic mixture in alloys. Vogt[4] calculated the ratio between quartz and feldspar in a number of analyses of graphic intergrowths of quartz with microcline, the latter mineral being also perthitically intergrown with various amounts of soda plagioclase. The ratios were constant enough to lead Vogt to conclude that the graphic granites represented eutectic mixtures. Slight disparities between analyses he attributed to slight variations in the compositions of the feldspars and to variations in the pressures under which the granites had crystallized. In many cases, especially in microscopic varieties, the graphic intergrowths are considered to be the end-products of crystallization.

In 1905, H. E. Johansson,[5] working mainly with Vogt's analyses, computed the molecular proportions of the quartz and feldspars present and arrived at the conclusion that these bore very simple numerical relations to each other. In graphic granites with dominant orthoclase the molecular ratio of feldspar to quartz was about 2:3. In an oligoclase graphic granite the proportion was about 1:2, and in an albite-quartz micropegmatite about 1:3.

Later Bygden[6] made a considerable number of other analyses of graphic granites with the special purpose of determining to what

[1] Vogt, *Die Silikatschmelzlosungen*, II, 117–35 (1903).

[2] See Harker, *The Natural History of Igneous Rocks*, 262–66, 270–72.

[3] See Teall, *British Petrography*, 401–2 (1888).

[4] *Op. cit.*, 120–21.

[5] H. E. Johansson, *Geologiska föreningens förhandlingar* (Stockholm, 1905), XXVII, 119.

[6] A. Bygden, "Ueber das quantitative Verhältnis zwischen Feldspar und Quartz in Schrift-Graniten," *Bulletin of the Geological Institution of the University of Upsala*, VII, 1–18 (1904–5).

extent the quartz-feldspar ratio is dependent upon the composition of the feldspar. He concluded that the ratio between quartz and feldspar bore no *regular* relationship to the composition of the feldspar. He believed that in most graphic granites definite ratios did exist between the proportions of feldspar and quartz but that these ratios were not always so simple as Vogt and Johansson had supposed.

TABLE SHOWING COMPOSITIONS OF GRAPHIC GRANITES

No.	Locality	Feldspar* Percentage	Quartz* Percentage	Molecular Percentages of Feldspar Components			Reference
				Orthoclase	Albite	Anorthite	
1.......	Skarpö	70.5	29.5	82.5	15.1	2.4	Bygden No. 7
2.......	Hitterö	66.0	34.0	77.6	21.6	0.8	Bygden No. 8
3.......	Voie, Arendal	74.7	25.3	73.8	24.0	2.2	Vogt No. 1
4.......	Elfkarleö	79.2	20.8	74.8	24.5	0.7	Bygden No. 6
5.......	Topsham, Me.	72.9	27.1	74.4	25.6	none	Bastin
6.......	Topsham, Me.	73.7	26.3				
7–8.....	Hitterö	75.3	24.7	69.1	28.5	2.4	Vogt Nos. 2 and 3
9.......	Reade	72.7	27.3	66.1	28.2	5.7	Vogt No. 4
10.......	Arendal	76.5	23.5	63.9	33.7	2.4	Vogt No. 5
11.......	Bedford, N.Y.	76.8	23.2	61.7	37.0	1.3	Bastin
A.......	Rödö	56.0	39.0	9.6	85.4	5.0	Bygden No. 9 (Holenquist)
B.......	Evje	68.3	31.7	12.4	76.0	11.6	Vogt No. 6
C.......	Ytterby	62.1	37.9	4.3	74.5	21.2	Bygden No. 11
D.......	Beef Island	81.7	18.3	4.6	68.0	27.4	Bygden No. 12

* Calculated from the analyses.

To supplement the small number of available trustworthy analyses the writer collected specimens of graphic granite from the Fisher feldspar quarry in Topsham, Maine, and from Kinkle's feldspar quarry in Bedford, N.Y. These were analyzed by Mr. Geo. Steiger in the laboratory of the U.S. Geological Survey. In order that the material analyzed should represent closely the true composition about 10-pound samples of the Maine occurrences were taken. These were pulverized, carefully mixed, and quartered down to convenient size for analysis. The New York specimen was a cleavage piece about 2×3×1 inches in size.

The ratio of quartz to feldspar in the analyses published by Vogt and Bygden and in the author's analyses are given in the table above.

In Fig. 3 the composition of the feldspars are plotted on triangular projection. The numbers on the diagram correspond to those in the table.

From the table and diagram it is at once evident that even among those graphic granites whose feldspars are almost identical in composition (such as Nos. 2 to 6) there are quite considerable variations

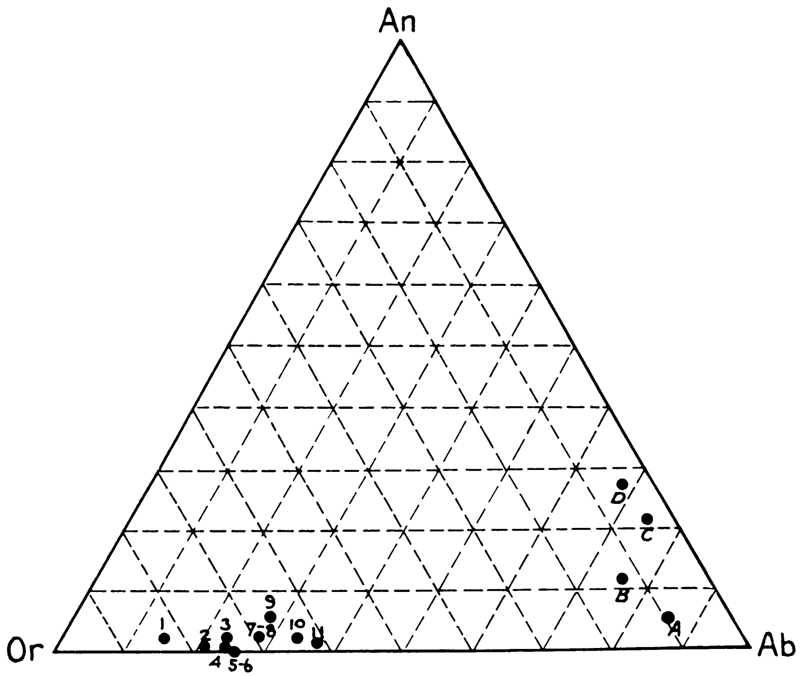

FIG. 3.—Three-component diagram showing the relationships between the molecular percentages of orthoclase, albite, and anorthite in the graphic granites tabulated above. The numbers and letters in table and diagram correspond.

in the quartz-feldspar ratio. In analyses Nos. 1, 2, 3, 7, 8, 10, and 11 (particularly in Nos. 1, 3, 7, 8, and 10) the percentage of anorthite is small and nearly constant, the only important variation being in the ratio between orthoclase and albite. No regular or consistent relationship is recognizable, however, between this ratio and the ratio between quartz and feldspar. The grouping of Nos. 1 to 11 near the lower line of the diagram signifies merely that the feldspar asso-

ciated with the orthoclase (or microcline) in graphic granites as in normal granites[1] is usually albite or oligoclase.

Both analyses and microscopic studies show that most graphic granites are mixtures of three minerals: (1) quartz, (2) orthoclase or microcline, and (3) a member of the isomorphous series of plagioclase feldspars. It should be pointed out moreover that if water or other gases were present, as it is almost certain they were, they formed additional components whose amount the analyses do not reveal but whose influence upon the proportions of the other constituents may have been great. If graphic granites crystallized from magmas of eutectic proportions, these were therefore eutectics of at least four components. *The above series of analyses, though suggesting that the proportions between the constituents of graphic granites are controlled by some laws, can hardly be regarded as proving their eutectic origin.* The theoretical value of such analyses, in elucidating the laws governing rock solutions, is impaired by the fact that they take no account of the gaseous components of the magmas.

Vogt[2] states that in many instances, especially when developed on a microscopic scale, the graphic intergrowths represent the last portions of the magma to crystallize. This fact he cites as in harmony with the conception that they represent eutectic residues. While this may be the true relation in some cases, in other cases the graphic granite was unquestionably not the last crystallization from the magma. In the Fisher feldspar quarry in Topsham, for example, where large masses of graphic granite pass gradually and irregularly into large areas of pure quartz and feldspar, the tests of Wright and Larsen (see p. 310) have shown that the quartz of the graphic intergrowths crystallized above 575° C., whereas the quartz of the large pure areas crystallized below 575°. The latter was therefore the later crystallization. The gem and cavity-bearing portions of the Maine pegmatites in almost every instance grade gradually into normal pegmatite containing abundant graphic granite. From the presence of cavities and of the rare minerals, from the general field relations, and from the fact that the quartz of the pockets and the gem-bearing portions wherever tested is of the low-temperature variety, there can

[1] See Clarke, "The Data of Geochemistry," *Bull. U.S. Geol. Survey No. 330*, 369.

[2] *Op. cit.*, 118.

be no reasonable doubt that these gem- and cavity-bearing portions rather than the adjacent graphic portions were the last parts of the pegmatite to crystallize.[1]

In considering the significance of the graphic intergrowths found in pegmatite it is necessary to consider not only the intergrowths of feldspar and quartz but also the almost equally regular intergrowths of muscovite and quartz, garnet and quartz, black tourmaline and quartz, etc. Since muscovite, tourmaline and garnet are less abundant in the pegmatites than feldspar, their intergrowths with quartz are also less abundant and usually of smaller size. Such intergrowths occur, however, scattered irregularly through practically all of the coarser pegmatite masses. If we adopt the usual conception of the eutectic as the residue of uniform composition and minimum freezing-point which is the last portion to crystallize, it is manifestly impossible to regard each of these intergrowths as representing a eutectic mixture, unless indeed several portions of the pegmatite magma are regarded as crystallizing more or less independently of the remainder of the mass.

Mineralogical provinces.—Most of the known pegmatites of Maine which are rich in sodium and lithium minerals, that is, the gem-bearing pegmatites, are restricted to a zone about twenty-five miles long and eight to nine miles in width extending in a northwesterly direction from Auburn in Androscoggin County to Greenwood in Oxford County. A second and much smaller area includes the Newry and Black Mountain localities in the northern part of Oxford County and differs from the larger area in that the gem minerals occur imbedded in the solid pegmatite and not in pockets. Within both areas the lithium-bearing phases form only a small proportion of the pegmatite present, most of which has the normal composition. The presence locally of certain masses of unusual composition is to be attributed either to a very minute excess of sodium and lithium

[1] In the tourmaline-bearing pegmatites of California, according to Mr. W. T. Schaller (oral communication), the zones characterized by cavities and by the presence of the gems and other rare minerals, which were almost certainly the last portions to crystallize, grade laterally without sharp break into graphic granite which borders one wall of these pegmatite masses. Occasional stringers of pegmatite bearing lithium minerals branch off from the main gem-bearing layer and cut the bordering graphic granite.

throughout the magma which gave rise to these pegmatites, over the percentages in bordering pegmatite magmas, or else to differing degrees of magmatic segregation in magmas whose average composition was similar. As already explained, quartz associated with lepidolite and clevelandite from the gem-bearing portion of one of these pegmatites showed low-temperature characters, and the unusual abundance of pockets indicates that these portions were richer than the normal in gaseous constituents, probably mainly water vapor. In general therefore the gem-bearing pegmatites were characterized by a higher percentage of sodium, lithium, and phosphorus than the normal pegmatites, and probably by more water vapor and a slightly lower temperature of crystallization.

The region characterized by pegmatites rich in fluorine minerals but not in the lithium minerals forms an area only a few miles across in the town of Stoneham and bordering parts of other towns in Oxford County and the town of Chatham, New Hampshire.

Bearing of broad geologic relations on genesis.—The broad geographic relationships of the granites and pegmatites are also significant of their relationship and origin. Many of the granite areas of the eastern portion of Maine are characterized by sharp boundaries, while most of the granite areas of southwestern Maine show very indefinite boundaries and are bordered by large areas of slates and schists which have been intruded by various amounts of granite-gneiss and pegmatite and by some granite and diorite. The contrast between the two types of contacts is well shown within the areas of the Penobscot Bay[1] and Rockland[2] folios. In many parts of the latter area, notably along the granite-schist contact from Bluehill village northward and from Bluehill Falls southwestward to Sedgwick, the granite preserves its normal medium grain up to the exact contact. In most places this contact is so sharp that it is possible to stand with one foot resting upon typical Ellsworth schist and the other foot resting on normal granite. Dikes and irregular intrusions of granite are not very abundant in the schists near the main granite masses, and flow-gneiss, pegmatite, and basic differentiations from the granite magma are almost entirely absent. In the Rockland quadrangle,

[1] *Geologic Atlas U.S.*, folio No. 149, U.S. Geol. Survey.

[2] *Ibid.*, folio No. 158.

on the other hand, the contact relations are wholly different, the change from pure granite to pure sediments taking place gradually through a transition zone of contact metamorphosed and injected sediments two to three miles in width. These transition zones include a great variety of rocks, slate, schist, injection gneiss, flow-gneiss, diorite, diabase, pegmatite, and granites of various textures, all associated in the most irregular manner so that it is impracticable to delineate them separately in ordinary geologic mapping. In western and southwestern Maine these transition zones are much broader than in the Rockland quadrangle and contain larger amounts of pegmatite and granite gneiss and smaller amounts of basic igneous rocks.

The contrast between the sharpness of certain granite contacts observed in the Bluehill region and the very gradual transitions observed in the Rockland quadrangle and farther southwest seem to be best explained on the hypothesis that the broad injected zones represent portions of the "roof" of granite batholiths, whereas the sharp contacts represent the sides of similar batholiths. The character of the rocks which are found in the two types of contacts lends support to this view. The more ready escape of water gas and other gases and their dissolved substances upward than laterally may explain the great abundance of pegmatite in the broad transition zones, inasmuch as the presence of such gases is believed to be the most important factor in the development of pegmatitic texture. It is a reasonable supposition that basic differentiation from the granitic magma would also be more rapid upward than laterally, and the abundance of diabase and diorite in certain of the transition zones may thus be accounted for. The hypothesis is also in accord with the low temperatures at which certain portions of the pegmatites appear to have crystallized, in comparison with the temperatures of crystallization of normal granites, and accords with the presence of numerous dikes of very fine-grained granite, some so fine as to be rhyolitic, in certain of the contact zones, and their absence about the sharper contacts.

Summary.—Field and laboratory studies of the Maine pegmatites indicate that all are in a broad way contemporaneous and are genetically related to the associated granites.

External conditions, though locally having some slight influence,

are not primarily responsible for the pegmatitic textures. The presence of the rarer elements seems to have had only a minor influence on the texture since in many typical pegmatites such elements appear entirely absent. Theoretical considerations and the presence of miarolitic cavities in certain pegmatites point to the gaseous constituents of the pegmatite magmas, especially water vapor, as the primary cause of their textures.

While certain facts, such as the pinch and swell phenomena observed in many pegmatite dikes in contrast with the parallel-walled character of most of the granite dikes, indicate somewhat greater mobility in the pegmatite than in the granite magmas, other facts, such as the sharpness of many of the contacts between pegmatite and schist, the absence of absorption along any of the contacts, the presence of angular schist fragments now surrounded by pegmatite, the small proportion by volume which the cavities bear to the whole pegmatite mass, the absence of notably greater contact metamorphic effects near pegmatite than near granite contacts, and the batholithic dimensions of some pegmatite bodies, all suggest that the difference in average composition between the granite pegmatites and the normal granites was perhaps not so great as has generally been supposed.

In his textbook on *Igneous Rocks* Iddings[1] in discussing the pegmatites says: "The amount of gases concentrated in such magmas was not many times that of the gases originally distributed throughout the magma from which the pegmatite was differentiated; possibly not more than ten times as much." The present writer would be inclined, in the case at least of the granite pegmatites of New England, to limit the gaseous content of these rocks still further.

The experiments of Messrs. Wright and Larsen on quartz from pegmatites from Maine and elsewhere indicate that some at least of the coarser pegmatites began to crystallize at a temperature slightly above the inversion-point of quartz (about 575° C.) and completed their crystallization somewhat below this temperature. It is probable that many of the finer-grained pegmatites crystallized wholly above 575° C.

The theory that the graphic intergrowths in pegmatites represent eutectic mixtures cannot be regarded as proven by the published

[1] Joseph P. Iddings, *Igneous Rocks* (1909), I, 276.

analyses. Certain field evidence is unfavorable to the theory that these are eutectics.

The broader field relations suggest that the large areas characterized by particular abundance of pegmatite intrusions constitute in reality the *roofs* overlying granite batholiths. Where more extensive erosion has exposed the flanks of such batholiths pegmatite masses in the bordering schists are not abundant.